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Review

# Biomechanical effects of valgus knee bracing: a systematic review and meta-analysis

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SUMMARY

To review and synthesize the biomechanical effects of valgus knee bracing for patients with medial knee osteoarthritis (OA). Electronic databases were searched from their inception to May 2014. Two reviewers independently determined study eligibility, rated study quality and extracted data. Where possible, data were combined into meta-analyses and pooled estimates with 95% confidence intervals (CI) for standardized mean differences (SMD) were calculated. Thirty studies were included with 478 subjects tested while using a valgus knee brace. Various biomechanical methods suggested valgus braces can decrease direct measures of medial knee compressive force, indirect measures representing the mediolateral distribution of load across the knee, quadriceps/hamstring and quadriceps/gastrocnemius co-contraction ratios, and increase medial joint space during gait. Meta-analysis from 17 studies suggested a statistically significant decrease in the external knee adduction moment (KAM) during walking, with a moderate-to-high effect size (SMD = 0.61; 95% CI: 0.39, 0.83; $P < 0.001$). Meta-regression identified a near-significant association for the KAM effect size and duration of brace use only ($\beta$, −0.01; 95% CI: −0.03, 0.0001; $P = 0.06$); with longer durations of brace use associated with smaller treatment effects. Minor complications were commonly reported during brace use and included slipping, discomfort and poor fit, blisters and skin irritation. Systematic review and meta-analysis suggests valgus knee braces can alter knee joint loads through a combination of mechanisms, with moderate-to-high effect sizes in biomechanical outcomes.



## Introduction

Knee braces designed to redistribute loads across the knee are available for patients with lower limb malalignment and knee osteoarthritis (OA) primarily affecting one compartment. Valgus braces that are designed to lessen the proportion of load on the knee medial compartment for patients with varus alignment are most common, given the increased load typically borne by that compartment during walking and the higher prevalence of medial knee OA[1,2]. Systematic review and meta-analysis of existing randomized trials suggest that valgus bracing can provide small-to-moderate improvements in pain and function[3]. However, the effect sizes vary largely depending on the study design, with the type of control intervention used as a comparator (e.g., a neutral brace) being particularly important[3]. Those results provide rationale for systematic review of the evidence supporting or refuting proposed biomechanical effects of valgus braces.

Multiple, and likely overlapping, mechanisms by which valgus braces alter knee joint biomechanics have been proposed[4–7]. These include both altering the distribution of load and decreasing the magnitude of load on the knee through improvements in malalignment, providing a valgus brace moment to counteract the knee adduction moment (KAM), increasing joint stability, lessening muscle co-contraction and improving proprioception[4–9]. Although informative, sample sizes for these studies are generally small and results vary considerably. Whether valgus braces can

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indeed provide the proposed beneficial biomechanical effects remain unclear. The uncertainty surrounding the effects of valgus bracing, both in terms of their proposed clinical effects and biomechanical mechanisms, is also reflected by the variable recommendations in clinical practice guidelines[10–19]. A systematic review with meta-analyses where possible would help clarify the biomechanical mechanisms underlying valgus bracing and may ultimately improve their design and effectiveness. Therefore, the purpose of this study was to review and synthesize the biomechanical effects of valgus knee bracing for patients with medial knee OA.

## Methods

### Literature sources and study selection

Electronic databases we searched from their inception to May 2014: The Cochrane Central Registry for Controlled Trials, MEDLINE, EMBASE, CINAHL, Scopus, ScienceDirect and Web of Knowledge. Searches used combined and/or truncated key terms including: "knee*", "osteoarthritis OR arthritis OR arthrosis", "brace* OR bracing", and "valgus brace* OR valgus bracing". A database search strategy is included in the Online supplement. Reference lists of potentially eligible articles were manually searched.

Peer-reviewed studies that examined the biomechanical effects of valgus knee braces in patients with medial compartment knee OA, published as full text, English language journal articles were included. There were no restrictions on study dates or design, the development or severity of knee OA, or on follow-up duration. Editorials, comments, letters, abstracts, review articles, theses and dissertations, and animal or cadaveric studies were excluded. A detailed protocol for this review has not been previously published.

### Determining inclusion

Studies that compared a measure indicative of the biomechanical effects of valgus bracing in the same group of patients before and after wearing the brace, with or without comparison to a neutral brace or lateral wedge foot orthotic, were included. Two reviewers (RFM and KML) blinded to journal title and authorship independently assessed eligibility in two stages. Title and abstracts were reviewed. Articles that met the eligibility criteria were then obtained as full manuscripts and reviewed. Disagreements between reviewers regarding article selection were discussed and consensus was achieved. Details of the literature search are reported using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[20].

### Outcome measures and data extraction

Using the longest follow-up period, two independent reviewers (RFM and KAM) extracted means and standard deviations before and after wearing a valgus knee brace when available. Outcome measures used to assess changes in biomechanics with brace use included knee joint kinematics, kinetics and electromyography during walking (i.e., gait analysis), the moment provided by the brace, directly measured joint compressive force, static and dynamic radiography, long-term changes in bone mineral density (BMD), joint position sense and standing balance[4–9]. In addition to measures evaluating biomechanical effects, data on patient-reported compliance and complications with brace use were also extracted. The same reviewers also extracted the following information from each study: study design, number of patients, patient demographics, duration of brace use, all biomechanical outcomes, and funding sources. Disagreements between reviewers regarding article selection were discussed and consensus was achieved.

Studies were first categorized according to study design. Definitions provided by the Cochrane Collaboration were used to define the studies as observational cohort studies or randomized trials[21]. An observational cohort study followed a defined group of participants over time (prospectively). A randomized clinical trial (RCT) randomly allocated participants to a treatment group and followed them over time (in parallel or crossover). Studies not fitting into these categories, but rather repeated biomechanical evaluations with and without wearing a valgus brace during a single test session, were simply defined as laboratory studies. Authors were contacted when information or data were not reported or were unclear.

### Quality assessment of included studies

Two reviewers (RFM and KAM) independently scored the methodological quality of each study using the Downs and Black scale that was modified to include 13 items to assess internal validity[22]. Each item scored 1-point if the item was satisfied. Disagreements between reviewers were discussed and consensus was achieved.

### Data analysis

Agreement between reviewers was evaluated using the kappa ($\kappa$) statistic. For the meta-analysis, pooled estimates and 95% confidence intervals (CI) for standardized mean differences (SMD) for change in outcomes were calculated using a random effects model. The SMD was calculated for paired samples using the within-patient change for patients in the valgus knee brace group divided by the pooled standard deviation. Reported sample sizes, pre- and post-intervention means, standard deviations, and/or level of significance were used. The size of the SMD was interpreted using Cohen's d[23]. For studies not reporting sufficient data, and where the authors could not provide data, we estimated values from figures or imputed missing data using the following approach. If a study reported significant findings with a non-exact $P$ value (i.e., $P < 0.05$ or $P < 0.01$), we assigned $P$ values of $P = 0.05$ and $P = 0.01$, respectively[21,24]. For non-significant findings reported with a non-exact $P$ value, a paired correlation value of $r = 0.5$ was used to calculate the SMD[25–28]. To evaluate the robustness of this imputation method, three sensitivity analyses were performed while using the highest or lowest reported correlation from included studies, and while excluding studies with imputed data. For studies reporting multiple changes in the external KAM, only the greatest change was included in the meta-analysis. For studies with multiple follow-ups, the last available follow-up was used. Publication bias was assessed using the Egger's regression test[29], and if present, adjustment was planned using a trim and fill method[30].

Heterogeneity was assessed using the $I^2$ statistic and Q statistic[28]. Significant heterogeneity was evaluated by meta-regression using six study characteristics identified a priori including duration of brace use, baseline varus alignment, brace angulation, study quality, year of publication, and funding source.

Complications with brace use were assessed quantitatively from event rates (proportions) using the number of events and total sample size for each study. Each meta-analysis was performed using the Comprehensive Meta-Analysis software program (V2, Biostat, Englewood, NJ, USA). All statistical tests were conducted at a significance level of $P < 0.05$, or the 95% CI failed to cross the line of no significance.

## Results

### *Study selection*

After removing duplicates, 519 studies were identified from the literature search, 102 full-text studies were screened and 30 studies evaluating biomechanical effects of valgus knee braces were included (Fig. 1). Inter-rater agreement was excellent for determining eligibility of titles and abstracts ($\kappa = 0.94$) and full-text studies ($\kappa = 0.85$). Of the 72 excluded studies, 11 only evaluated patient-reported outcomes of valgus knee braces (i.e., no biomechanical outcome). After extracting data for 30 full-text studies, disagreement was recorded for 11 (36%) studies and a consensus was met following a joint reassessment. The outcome measures from all 30 studies were examined descriptively. Data from 17 studies were combined in a meta-analysis.

### *Study characteristics*

Characteristics of the included studies are described in Table I[9,31–59]. Data from 589 subjects were reported and 478 subjects with knee OA were prescribed a valgus knee brace. Age ranged from 21 to 85 years. Of the 22 studies that reported sex, 210 (58%) males and 154 (42%) females were included. Knee OA severity was only reported in 13 studies. Sixteen studies were primarily laboratory studies testing on a single day, ten studies were prospective cohort designs and four studies were randomized controlled trials. No studies evaluated structural measures of disease progression. Authors were contacted for eight articles[34,39,47,48,50,56,58,59]. Seven authors responded. Five authors were able to provide additional data not reported in the original study.

Sixteen studies investigated the effects of a single brace set at a single valgus angulation[32–35,37–41,45,47,50,53,57–59], while five studies compared one valgus brace to another valgus brace, or to the same brace in multiple degrees of valgus angulation[42–44,51,52]. Seven studies used a control knee brace not intended to apply a valgus moment and alter distribution of joint loads[31,36,43,46,48,52,54]; and five studies compared valgus bracing to lateral wedge insoles[9,49,51,55,56]. Control knee braces included loose or poorly fixated braces, or anterior cruciate ligament (ACL) stabilizing braces.

Nine different brace angulations were used across 23 studies (of 30) and the remaining seven studies did not specify the brace

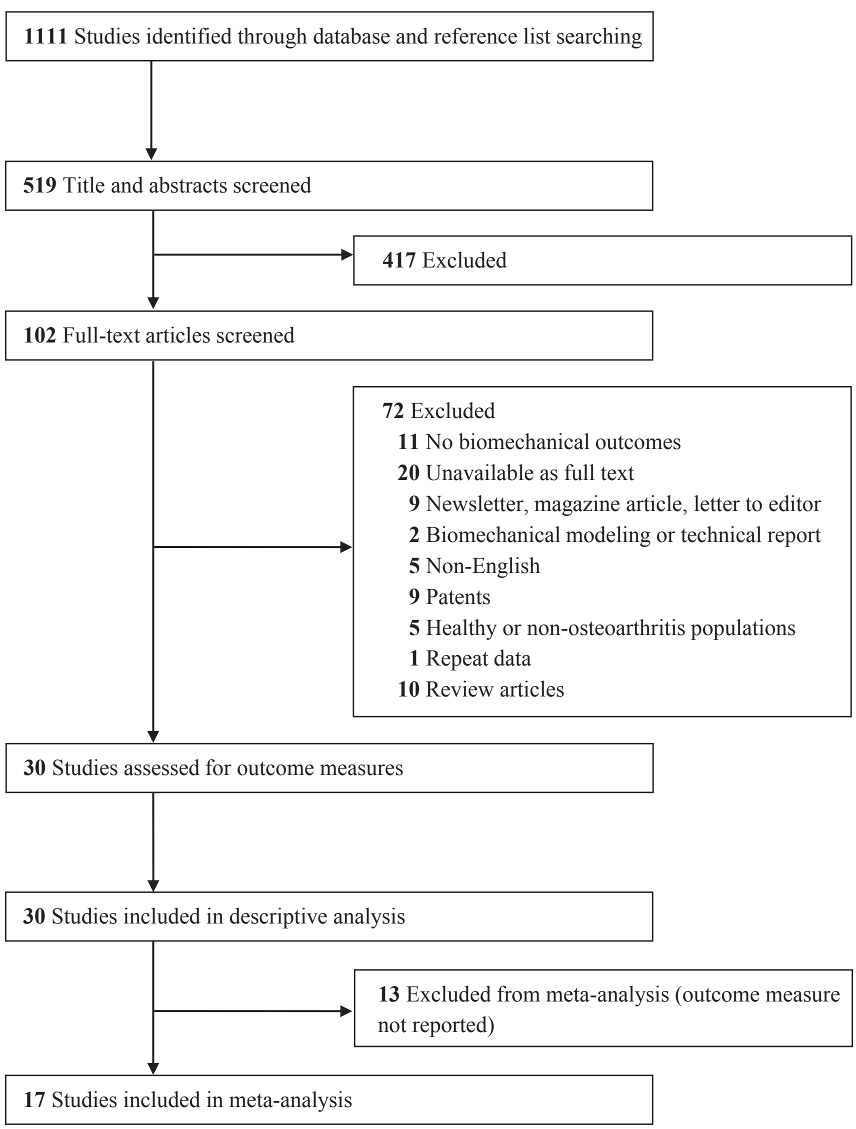


**Fig. 1.** The 2009 PRISMA Flowchart. Thirty studies were included for descriptive and qualitative analysis.

**Table I**
Demographics and study characteristics ($n$ = 30)

| Author (year) | $n$ | Age* | Varus alignment (°)* | KL grade of severity | Duration (wks) | Biomechanical outcomes | Funding source |
|---|---|---|---|---|---|---|---|
| Horlick *et al.* (1993)[31,†] | 40 | 46 (34–69) | – | – | 6 | Alignment Joint space | Generation II |
| Lindenfeld *et al.* (1997)[32,‡] | 11 | 47.5 ± 14 | – | – | 4–6 | KAM<br>KFM/KEM | Cincinnati Sport Medicine Research and Education Foundation |
| Matsuno *et al.* (1997)[33,‡] | 20 | 76.6 (58–84) | 185.1¶ | 3, $n$ = 13<br>4, $n$ = 4<br>5, $n$ = 3 | 52 | Alignment | Generation II |
| Hewett *et al.* (1998)[34,‡] | 20 | 41 (21–78) | – | – | 52 | KAM<br>KFM/KEM | Bledsoe Brace Systems, Cincinnati Sport Medicine Research and Education Foundation |
| Katsuragawa *et al.* (1999)[35,‡] | 14 | 69 (57–80) | – | – | 12 | BMD | Unclear |
| Komistek *et al.* (1999)[36,§] | 15 | – | – | – | – | Joint space<br>Alignment | Bledsoe Brace Systems |
| Self *et al.* (2000)[37,§] | 5 | 49 (40–55) | – | – | – | KAM<br>Brace force | – |
| Birmingham *et al.* (2001)[38,§] | 20 | 59 ± 9 | Males: 8.4 ± 4.3#<br>Females: 8.0 ± 4.3# | – | – | Proprioception<br>Balance | Medical Research Council, Physiotherapy Foundation of Canada |
| Pollo *et al.* (2002)[39,§] | 11 | 53.2 ± 9.8 | – | – | 2 | KAM<br>Brace moment | Generation II |
| Barnes *et al.* (2002)[40,‡] | 30 | 61.66<br>49.33 | – | 2.66<br>3.11 | 8 | Joint space<br>Alignment | – |
| Anderson *et al.* (2003)[41,§] | 11 | – | – | – | – | Joint force | New Zealand War Pensions Medical Research Trust Fund |
| Nadaud *et al.* (2005)[42,§] | 5 | – | – | – | – | Joint space | – |
| Dennis *et al.* (2006)[43,§] | 40 | – | – | 4, $n$ = 40 | – | Joint space | Bledsoe Brace Systems |
| Draganich *et al.* (2006)[44,†] | 10 | 50.8 ± 5.4 | 6.4 ± 3.0# | – | 4–5 | KAM<br>Alignment | DonJoy Orthopedics |
| Gaasbeek *et al.* (2007)[45,§] | 15 | 52 ± 11 | 5.1 (2–11)# | – | 6 | KAM | POM, Nijmegen, The Netherlands and Bauerfeind GmbH |
| Ramsey *et al.* (2007)[46,‡] | 16 | 54.9 ± 8.8 | 7.5 ± 3.3** | – | 2 | Muscle activation<br>Alignment | National Center for Research Resources, National Institutes of Health |
| Schmalz *et al.* (2010)[47,§] | 16 | 56 ± 9 | – | 1, $n$ = 1<br>2, $n$ = 5<br>3, $n$ = 7<br>4, $n$ = 3 | 4 | KAM<br>Brace moment<br>KFM/KEM | – |
| Fantini Pagani *et al.* (2010)[48,‡] | 11 | 55.5 ± 5.5 | – | 2, $n$ = 6<br>3, $n$ = 5 | 2 | KAM<br>Angular Impulse<br>Brace moment | Institute of Biomechanics of German Sport |
| van Raaij *et al.* (2010)[49,†,‖] | 91 | 54.9 ± 7.4 | 6.9 ± 3.6# | 1, $n$ = 22<br>2, $n$ = 7<br>3, $n$ = 17 | 6 | Alignment | – |
| Toriyama *et al.* (2011)[50,§] | 19 | 68.4 ± 7.8 | 184.8 ± 3.33¶ | 2, $n$ = 5<br>3, $n$ = 13<br>4, $n$ = 1 | – | KAM<br>KFM/KEM | – |
| Fantini Pagani *et al.* (2011)[51,§] | 10 | 57.5 ± 7.1 | 2.1 ± 1.2** | 2, $n$ = 6<br>3, $n$ = 4 | – | KAM<br>Angular impulse<br>Alignment<br>Brace moment | Institute of Biomechanics of German Sport |
| Kutzner *et al.* (2011)[52,§] | 3 | 65 ± 5.6 | 2.67 ± 1.53# | – | – | Joint force | Deutsche Arthrose-Hilfe, Zimmer GmbH, Deutsche Forschungsge-meinschaft |
| Esrafilian *et al.* (2012)[53,§] | 2 | 53 | – | – | – | KAM<br>Alignment | – |
| Fantini Pagani *et al.* (2012)[54,§] | 12 | 56 ± 4.6 | – | – | – | Muscle activation | Institute of Biomechanics of German Sport |
| Moyer et al. (2013)[9,§] | 16 | 55 ± 7 | 6.6 ± 3.3# | 1, $n$ = 2<br>2, $n$ = 5<br>3, $n$ = 6<br>4, $n$ = 3 | 24 | KAM<br>Angular impulse | – |
| Arazpour *et al.* (2013)[55,‡,‖] | 24 | 58.8 ± 2.2 | – | 1, $n$ = 5<br>2, $n$ = 7 | 6 | KAM | – |
| Jones *et al.* (2013)[56,†] | 28 | 66.3 ± 8.2 | 6.6 ± 4.1** | 2, $n$ = 10<br>3, $n$ = 18 | 2 | Alignment<br>KAM<br>Angular impulse | – |
| Della Croce *et al.* (2013)[57,§] | 18 | 68 ± 9 | – | – | – | KAM | – |
| Johnson *et al.* (2013)[58,‡] | 10 | 60 (44–85) | – | 2 or 3 | 12 | KAM | – |
| Larsen *et al.* (2013)[59,‡,‖] | 46 | 63.7 ± 10.6 | 3.28 ± 4.48** | 1 or 2, $n$ = 11<br>3 or 4, $n$ = 12 | 8 | KAM<br>Alignment | VQ Orthocare |

KL = Kellgren and Lawrence.
* Age and alignment are reported as mean ± standard deviation or mean (range).
† Randomized controlled trial: randomly allocates participants to a group and follows them over time.
‡ Observational cohorts: follows a single, defined group of participants over time.
§ Experimental study design with cross-sectional analysis: ideal testing conditions at a single point in time while controlling for other variables.
‖ Grade of severity reported only for patients wearing a valgus knee brace.
¶ Static measures of alignment using X-ray anatomic angle.
\# Mechanical axis angle.
** Motion capture system knee adduction angle.

angulation. Braces were described as off-the-shelf (i.e., pre-made and available in a number of predetermined sizes)[36,42–44,49,57], or custom (i.e., customized to the individual patient based on limb size and morphology)[9,32,33,37,44,47,55,58,59]. Angulations were described as neutral[31,36,46,48,52,54]; 10°[31]; 8°[39,51,52]; 6°[56]; and 4°[38,39,46,48,52,54].

*Quality assessment of included studies*

Inter-rater agreement for each item of the methodological quality assessment was moderate to high ($\kappa$ = 0.72–0.91). The mean quality appraisal score was 6.8 ± 1.4 (range: 4–9). Most studies received a score of zero for blinding and concealing randomization until recruitment was completed. As expected, blinding subjects and assessors was a substantial challenge to bracing intervention studies, but is of questionable significance given the biomechanical measurements investigated. No studies were excluded on the basis of quality appraisal. Results from the assessment tool can be located in the Online supplement.

*Outcomes measures*

*Frontal plane kinetics*

Seventeen studies (of 30) reported the effect of the brace on the external KAM during walking. Twelve studies (of 17) reported the overall peak KAM[32–34,37,39,44,45,53,55,57–59] while five studies reported the first and second peak KAMs separately[9,48,50,51,56]. Extracted data were analyzed and combined in a meta-analysis ($n$ = 218). Individual and pooled SMDs for changes in the external KAM are illustrated in Fig. 2. Adjusting the pre-post correlation, or excluding studies with imputed data, had minimal effect on outcomes. Overall, there was a moderate-to-large, statistically significant difference favoring the valgus brace group for improvement in the KAM (SMD, 0.61; 95% CI, 0.39 to 0.83, $P$ < 0.001; $I^2$ = 51.2%; $P$ = 0.008) (Fig. 2). Asymmetry in the funnel plot was observed and the Egger's regression test was positive for significant evidence of publication bias (intercept = 2.82, 95% CI: 1.11, 4.52; $P$ = 0.002) (Fig. 3). Using the trim and fill method, the adjusted SMD was 0.41 (95% CI: 0.17, 0.66).

A meta-regression analysis examined six study characteristics to potentially explain the significant heterogeneity among biomechanical studies evaluating the external KAM (Table II). There were no significant associations of treatment effect size with baseline varus alignment, brace angulation, study quality, year of publication, or funding sources. The duration of brace use approached a statistically significant association with treatment effect size ($\beta$, −0.01; 95% CI: −0.03, 0.0007; $P$ = 0.06), with longer durations of brace use associated with smaller treatment effects.

Five studies (of 30) described the valgus moment provided by the brace to directly oppose the external KAM[37,39,47,48,51]. One study (of five) reported a maximum valgus brace force of 60 N, which remained fairly constant throughout stance[37]. Four studies (of five) described the valgus moment created by the brace, and each suggested that greater valgus moments were associated with greater valgus angulations or strap tensions at both the first and second peaks of the KAM[39,47,48,51]. One study also reported the valgus brace moment relative to the magnitude of the KAM, suggesting that the mean maximum valgus moment generated by the brace accounted for approximately 10% of the external KAM during non-brace walking[47].

*Sagittal plane kinetics*

Four studies (of 17 studies that reported results for the external KAM) also described the effects of valgus knee bracing on the sagittal plane moment[32,34,47,50]. Two studies[32,34] reported no significant difference with and without wearing the brace, while the other two studies reported variable results. Toriyama *et al.*[50] reported significant changes for both peak flexion and extension moments during stance, however; the increase in knee flexion moment (KFM) observed by Schmalz *et al.*[47] was not significantly different with and without wearing a valgus knee brace. Although sagittal plane kinetics were not evaluated, Pollo *et al.*[39] emphasized

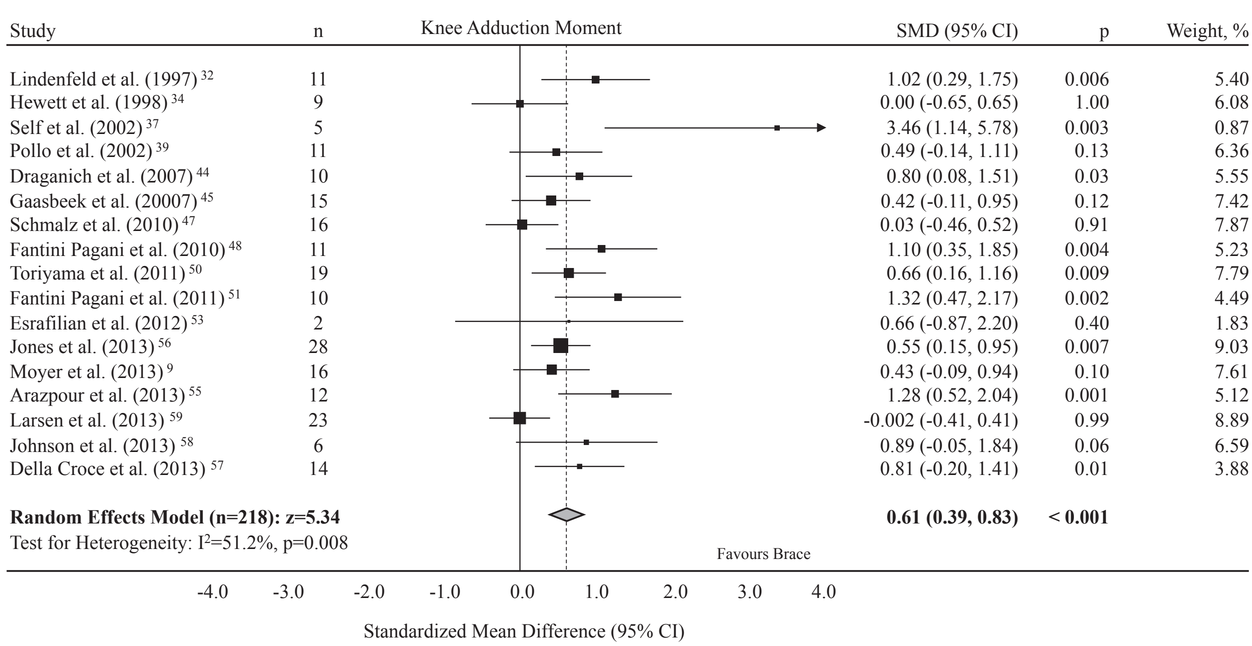


**Fig. 2.** SMD and 95% CI for the external KAM during walking with and without a valgus knee brace. The diamond represents the pooled effect size using a random effects model. The vertical line at 0 represents no difference. Data to the right of 0 represent a decrease in the peak external KAM. According to the $I^2$ and Q statistic ($P$ value), heterogeneity was moderate and significant.

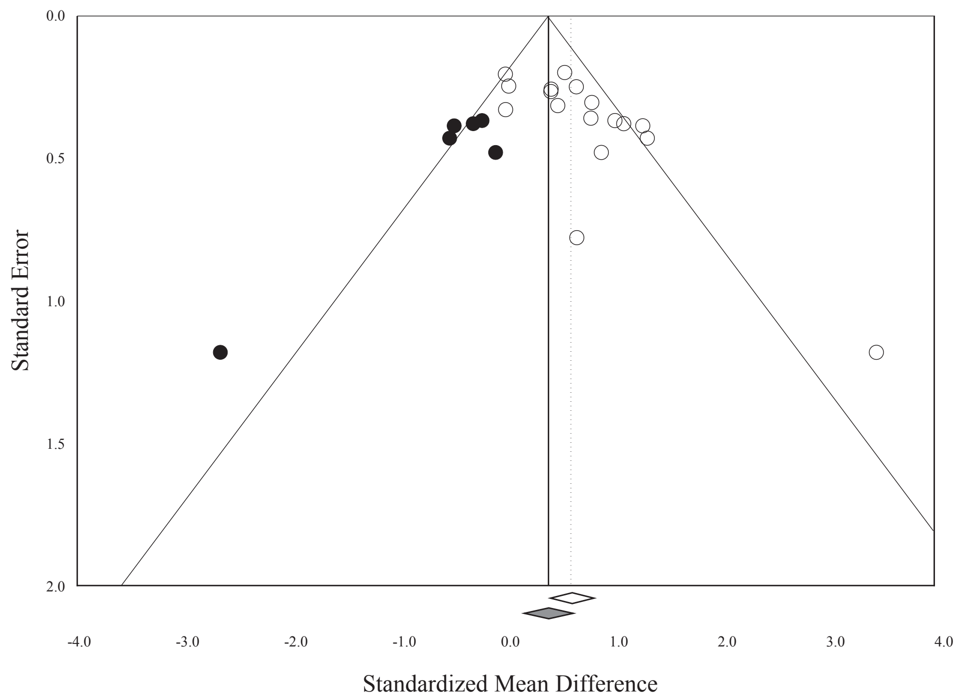


**Fig. 3.** Funnel plot representing publication bias across seventeen studies. The white and gray diamonds represent the observed and adjusted effect sizes for the KAM, respectively.

that consideration of knee flexion and extension moments (KFM/KEM) is important to better understand the effects of valgus braces.

*Medial compartment joint space*

Five studies (of 30) reported the effect of valgus knee bracing on medial compartment joint space[31,36,40,42,43]. Two studies used standing, hip-to-ankle anteroposterior (AP) radiographs and reported no significant difference in medial joint space between braced and non-braced conditions[31,40]. Means or measures of variability were not reported. Three studies (of five) used fluoroscopic gait analysis to measure knee joint space during walking[36,42,43]. Two studies (of three) reported statistically significant increases in condylar separation while wearing the brace[36,43]. The average increase in medial compartment separation (mean ± SD) for both studies ($n = 15$, $n = 40$)[36,43] was 1.3 mm ± 1.8 mm, respectively. In only those patients that had reported improvements in pain (12/15)[36] or an increase in joint space (31/40)[43], the respective average increase in medial compartment separation approached 2.0 mm and 1.7 mm. One study (of three) did not report whether the change in condylar separation was statistically significant (range: 0.2–0.8 mm)[42].

**Table II**
Meta-regression analysis of study characteristics potentially related to heterogeneity*

| | $\beta$ (95% CI) | $P$ |
|---|---|---|
| Duration of intervention use (weeks) | −0.01 (−0.03, 0.0007) | 0.06 |
| Varus alignment† | −0.01 (−0.12, 0.10) | 0.82 |
| Angulation of the brace | 0.06 (−0.14, 0.26) | 0.55 |
| Funding source | −0.01 (−0.26, 0.29) | 0.94 |
| Quality of the study | −0.05 (−0.20, 0.10) | 0.53 |
| Year of publication | −0.001 (−0.04, 0.04) | 0.96 |

* Each study characteristics was evaluated individually against effect size.
† Only seven studies that reported the knee adduction moment before and after brace use reported lower limb alignment at baseline.

*Lower limb malalignment*

Eleven studies (of 30) reported effects on lower limb varus alignment[31,33,36,40,44,46,49,51,53,56,59]. Five studies used the knee adduction angle calculated from three-dimensional gait analysis[46,51,53,56,59]. Non-significant decreases[46,59] and significant improvements in lower limb alignment (2.6°)[56] were reported. One study (of five) reported significant and non-significant improvements in lower limb alignment when patients wore an 8° and 4° valgus brace, respectively[51]. One study was excluded from further analysis because the values reported occurred during the swing phase of gait[53]. One study used fluoroscopic gait analysis and reported a decrease in varus alignment (2.2°) in 80% of patients ($n = 12/15$)[36]. Five studies used the hip–knee–ankle or femorotibial angle (FTA) measured on standing AP radiographs[31,33,40,44,49]. Non-significant decreases[31,40,49] and significant improvements in lower limb alignment (1.4°)[33] were reported. One study (of five) reported significant and non-significant changes in lower limb alignment when patients wore a custom fit and off-the-shelf brace, respectively[44]. Across nine (of 11) studies, the change in varus alignment ranged from 0° to 2.6°.

*Muscle co-contraction*

Two studies (of 30) examined the effects of a valgus brace on muscle co-contraction during walking[46,54]. Ramsey *et al.* (2007)[46] and Fantini Pagani *et al.* (2012)[54] reported decreases in co-contraction ratios for the following muscle pairs: vastus medialis-medial hamstrings (VM-MH), vastus lateralis-lateral hamstrings (VL-LH), vastus medialis-medial gastrocnemius (VM-MG) and vastus lateralis-lateral gastrocnemius (VL-LG). Ramsey *et al.* (2007)[46] observed a reduction in VM-MH with a 4° brace and VL-LH with both a neutral and 4° valgus setting (100 ms prior to initial contact through to the first peak KAM). No changes were observed for either VM-MG or VL-LG co-contractions. Reductions in VM-MH and VL-LH were also reported by Fantini Pagani *et al.* (2012)[54] for both neutral and 4° brace settings; however, these findings were only noted during the pre-activation phase of the gait cycle (150 ms before heel contact). During the loading phase (0–15% stance), reductions in VL-LG were also observed with the 4° brace. No changes were observed for VM-MG co-contractions.

*Proprioception*

One study (of 30) evaluated the effects of valgus bracing on measures of proprioception[38]. Birmingham *et al.* tested patients' abilities to actively replicate target knee joint angles, while blindfolded and in a seated position, and tested single-limb standing balance while standing directly on a force platform and while standing on a foam mat placed over the platform. Statistically significant improvements were observed for the joint repositioning test only. Although improvements in the one measure of proprioception were noted, the authors also questioned its relevance and carry-over to weight-bearing, functional activities.

*Direct measures of tibiofemoral contact force*

Two studies (of 30) examined the effects of a brace on direct measures of joint loading *in vivo*[41,52]. Anderson *et al.* (2003)[41] reported no significant difference on medial compartment load during standing with and without a brace when tested using Tekscan pressure sensors inserted arthroscopically. Authors suggested that their results might be attributable to sensors shifting. Kutzner *et al.* (2011)[52] reported decreased medial compartment force during walking with a brace when tested using telemetric implants in three patients after total knee arthroplasty. In neutral, 4° and 8° valgus brace settings, contact force was reduced by 10%, 18% and 23% respectively at the first peak KAM, and was reduced by 9%, 24%, and 30% respectively at the second peak KAM.

*BMD*

One study (of 30) reported changes in BMD after 3 months of brace use[35]. BMD increased 3% and 7% in the medial and lateral tibial condyles, respectively.

*Dosage and frequency of brace use*

Thirteen studies reported details regarding instructions for brace use. Instructions included wearing the brace all day[44,45,59], during activity[9,31,56,39], as needed[34,40,49] or at least 30 min per day[58]. Two articles indicated that a clinician fit the brace and provided instructions, but did not specify type or frequency of use[46,47]. Twelve studies reported patient compliance with brace use at the longest follow-up period (2–52 weeks), ranging from 29 to 100% of patients[31,33,34,40,44–47,49,55,56,58]. Definitions for patient compliance varied widely.

*Patient-reported complications*

Six studies (of 30) reported difficulties experienced by patients using a brace. Event rates with 95% CI are summarized in Fig. 4. Statistically significant heterogeneity prevented data pooling. The reported difficulties included slipping[47], instability or discomfort[40,46,52,57], and constraining or poor fit[40,49]. Additional complications resulting from brace use included skin irritation[49], and blisters[49].

## Discussion

The present systematic review with meta-analysis suggests that valgus knee braces can significantly alter knee joint biomechanics during walking, through multiple mechanisms. Studies suggest that valgus knee braces can significantly decrease direct measures of medial compartment load[52], indirect measures representing the distribution of loads across the knee[9,32,37,39,44,45,48,50,51,55–58], muscle co-contraction[46,54], and increase medial joint space during gait[36,42,43]. The changes in BMD observed over time are also consistent with these alterations in joint load[35]. Potential mechanisms by which valgus braces alter loads include the application of a valgus moment at the knee to directly oppose the external KAM, with or without an alteration in frontal plane alignment of the lower limb, and/or the provision of increased knee joint stability that enables less muscle co-contraction. The most commonly supported mechanism is that a valgus brace opposes the external KAM that exists during walking[37,39,47,48,51]. Observations of greater reductions in the KAM with larger valgus brace angulations are consistent with this mechanism[51,52]. Importantly, the inconsistent changes in a patient's lower limb frontal plane alignment with a valgus brace do not coincide with consistent decreases in medial compartment loads. This finding suggests a change in alignment is

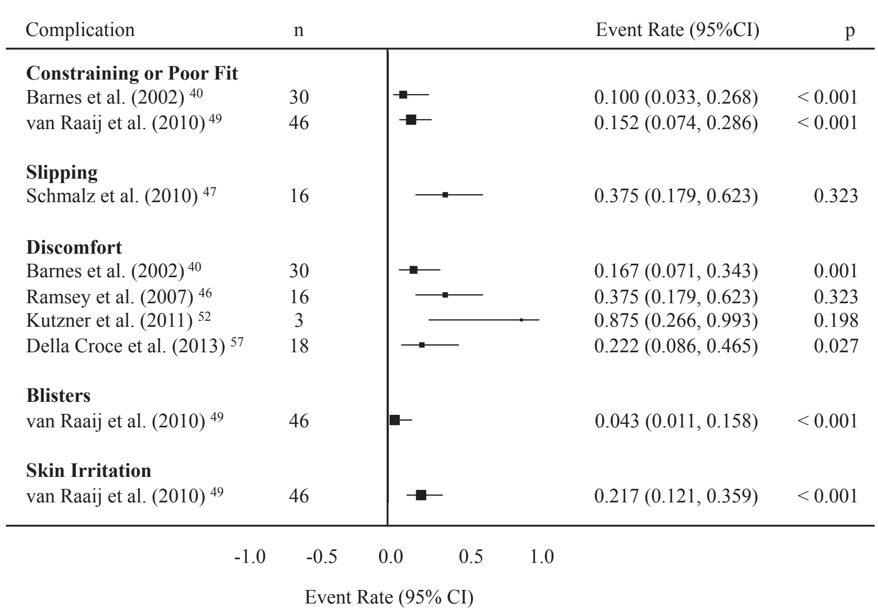


**Fig. 4.** Event rates and 95% CI for difficulties and complications during brace use. Significant heterogeneity prevented data pooling.

not necessarily required to shift load away from the medial compartment[31,36,40,44,46,49]. Alternatively, loads may be transferred from the medial compartment to the brace. Without a consistent change in lower limb alignment, transferring load to the brace may not necessarily lead to observable decreases in the KAM[39]. A less commonly suggested mechanism is that the brace stabilizes the knee and thereby enables decreased muscle co-contraction[46,54]. Observations of decreased co-contraction[46,54] with braces in neutral angulation are consistent with this mechanism. Few studies consider the biomechanical effect of bracing in the sagittal plane and report inconsistent findings for the flexion and extension moments. The inconsistent findings and suggestions that both the knee adduction and flexion moment contribute to future disease progression highlight a need for future investigations of valgus bracing beyond the frontal plane[39,60,61]. Based on the studies reviewed, valgus braces likely provide a combination of biomechanical mechanisms, acting in concert.

The importance of the observed biomechanical effects remains controversial. When described as a pooled effect size (Fig. 2: SMD, 0.61; 95% CI, 0.39 to 0.83, $P < 0.001$), the decrease in the external KAM can be considered moderate-to-high. After adjusting for publication bias, the pooled effect size was reduced somewhat, but can still be considered moderate (SMD, 0.41; 95% CI, 0.17, 0.66). Importantly, the external KAM represents the medial-to-lateral distribution of knee joint load rather than the actual force on the medial compartment[52,62], and proposed beneficial decreases in the KAM must be interpreted cautiously in situations where the total joint contact force may increase[52,62,63]. When considering the other biomechanical measures investigated, the fact that four studies reported small to no change in the external KFM[32,34,47,50], two studies suggested a decrease in knee extensor and flexor muscle co-contraction[46,54], and two studies reported an increase in medial joint space[36,43], these overall findings are consistent with directly measured decreases in medial contact force with valgus brace use. The magnitude of these effects remains unclear, however, with some authors suggesting the size of the decrease in load on the medial compartment observed with bracing is too small to be of much benefit, while other authors suggesting even small changes in knee joint loading may be important given the thousands of steps taken per day[9,32,45,48,51,55,56].

Although these biomechanical results are generally encouraging, they are tempered substantially by the available data on patient compliance. Reasons for poor compliance are numerous and may relate to the reported difficulties experienced with brace use (Fig. 4). Consistent reports of decreased brace use over time[40,51,64,65] may explain the significant association observed between the duration of brace use and treatment effects. As the duration of brace use increases, patient compliance decreases, limiting overall treatment effects. Patient characteristics, fading motivation for treatment adherence, and brace effectiveness combated by disease progression, are speculated as sources for diminishing treatment effects with prolonged use. Similarly, biomechanical studies have previously indicated that greater valgus angulations in the brace create greater reductions in the external KAM[51,52]. Unfortunately, greater valgus angulations are also associated with less comfort and may not be tolerated by the patient for prolonged durations[39,52,54]. The current regression analysis did not show a significant association between brace angulation and treatment effect, possibly due to poorer patient compliance associated with discomfort. If bracing is to play a larger role in the treatment of patients with knee OA, further research is required to determine optimal dosage. Additionally, exploring the effects of different brace angulations, durations of use, and the combined use of different types of orthoses to achieve larger biomechanical effects while maintaining patient comfort is warranted[9,66].

### *Limitations of this review*

Only studies that evaluated the effects of valgus knee bracing during level walking were included in this review. Data during stair use, from two studies that also evaluated the biomechanical effects of valgus bracing during gait, were excluded[44,52]. Both studies showed significant reductions of the KAM during stair use with a custom vs off-the-shelf brace[44] or brace with large vs small angulations[52]. Studies varied in design, disease severity of patients, brace type and data collection and analysis procedures. Although moderate heterogeneity was observed, the meta-regression only identified potential effects of different study methods (e.g., duration of brace use) on the present findings and should be acknowledged. Additionally, adjusting for publication bias using the trim and fill method assumes funnel plot symmetry and that an asymmetrical plot is the result of absent negative or undesirable findings. Considerable variation in patient response was consistently observed across studies highlighting the heterogenous nature of knee OA and the need for appropriateness criteria for non-surgical treatments. Furthermore, some patients may respond better to valgus braces than others. Current reports of subgroup data lack consistency; therefore identifying those patients likely to respond best is limited[36,49,65,67,68].

## Conclusions

This systematic review with meta-analysis suggests valgus braces can alter knee joint biomechanics through a combination of mechanisms, with the preponderance of previous studies reporting moderate-to-high effect sizes in the measures evaluated. Findings are tempered substantially by uncertainty in the clinical benefit of the effect sizes reported, and the consistent reports of poor compliance with long-term brace use. Identified gaps in the literature requiring further research include optimal dosage (i.e., the angular correction, valgus moment provided by the brace, and the duration of use) while balancing patient comfort, patient characteristics of those who are likely to respond best, effects on disease progression and economic evaluations.

## Contributors

Drs Moyer and Birmingham take responsibility for the integrity of the work as a whole. All authors had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

Conception and design: Moyer, Birmingham, Bryant, Giffin.

Collection and assembly of data: Moyer, Marriott, Leitch.

Analysis and interpretation of the data: Moyer, Birmingham, Bryant.

Drafting and final approval of the article: Moyer, Birmingham, Bryant, Giffin, Marriott, Leitch.

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Funders had no involvement with design and conduct of the study; collection, management, analysis, and interpretation of the data; and preparation, review, or approval of the manuscript.

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None.

**Competing interest statement**
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**Supplementary data**

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.joca.2014.11.018.

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